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Impact of a CP Violating Higgs: from LHC to Baryogenesis

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We observe a generic connection between LHC Higgs data and electroweak baryogenesis: the particle that contributes to CP violating hgg or $h\gamma\gamma$ vertex would provide a CP violating source during first order phase transition. It is illustrated in the 2HDM that a common CP violating phase controls the lightest Higgs properties at the LHC, electric dipole moments and the CP violating source for electroweak baryogenesis. We perform a general parametrization of Higgs effective couplings and a global fit to the LHC Higgs data. Current LHC measurements prefer a nonzero CP violating phase for $\tan\beta \lesssim 1$ and EDM constraints still allow an order one phase for $\tan\beta \sim 1$, which gives sufficient room for generating the correct cosmic baryon asymmetry. We also give some prospects in the direct measurements of CP violation in the Higgs sector at the LHC.

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Introduction. The presence of CP violation is always an important aspect in particle physics, which unambiguously leads to discoveries and open questions. In the Standard Model (SM), the CP violations in the K and B-meson systems have established the Cabbibo-Kobayashi-Mskawa (CKM) matrix. Sakharov [1] has observed that CP violation is essential for creating the apparent asymmetry between matter and anti-matter in our universe. Unfortunately, the CP phase in the CKM matrix is always accompanied with huge suppression from the large quark mass hierarchy when used to generate baryons. Therefore, the searching for other sources of CP violation would be indispensable for beyond SM physics.

The observation of a SM Higgs-like boson at the Large Hadron Collider (LHC) with a mass at around 125 GeV was announced last summer [2]. Since then, more data has been accumulated [3, 4] and more sophisticated analysis has been carried out based on various Higgs production and decay channels mostly assuming CP conservation [5], with only few exceptions [6, 7]. If CP is violated, both dimension five CP even and odd operators would contribute to $gg \to h$ and $h \to \gamma\gamma$ processes without interference. One would expect the results of the Higgs global fits to be different in structure from previous studies. Interestingly, the same source of CP violation would contribute to fermion electric dipole moment (EDM) [8], and the interplay between the Higgs properties and low energy constrains would be highly non-trivial.

The CP violation source manifest in the higher dimensional Higgs coupling and EDM operators can be mediated by a weak-scale particle X with sizable Higgs coupling. This can have a intrinsic connection to baryogenesis in the early universe. The most familiar examples include the top quark or gaugino-Higgsinos. Generally, a CP violating $hX\bar{X}$ vertex suggests that mass of X carries a phase. In the presence of a strong first-order electroweak phase transition, such CP violating phase would become space-time dependent as X and $\bar{X}$ pass through the bubble wall, and the change in the phase is physical. A chiral charge will be created by interacting with the wall, which then diffuse into the unbroken phase and convert into a net baryon number by weak sphalerons. It is definitely appealing if baryogenesis can be explained with the knowledge of electroweak scale physics. Hence after the Higgs discovery with more precise measurements on the structure of Higgs boson effective couplings, we enter a territory to measure or constrain the possible CP violating sources responsible for the baryon asymmetry in our universe.

In this letter, we perform a first study on the direct connection between the latest LHC results on Higgs properties and the baryon number generation from a common CP violating phase. We work in a Two-Higgs-Doublet Model (2HDM) and the CP violating mediator X is identified as the top quark. We study the case when the lightest Higgs boson, with mass 125 GeV, is a mixture of CP even and odd states. We derive the modified Higgs coupling to other SM particles, and perform a global fit to the current data and extract the constraints on such phase, which is still allowed to be nonzero, and even favored to be large with $\tan\beta \lesssim 1$. We study the electron and neutron EDMs and find the constraints on the same CP phase can be alleviated due to a cancellation with $\tan\beta \sim 1$. The 2HDM framework with such a CP phase is capable of providing all the essential ingredients for electroweak baryogenesis. We show the correct baryon asymmetry of the universe can be generated in the above parameter space. The future advances in precise measurements of Higgs properties, EDMs and refinements in electroweak baryogenesis calculations are anticipated to offer further interplays and pave the way for the genuine origin of CP violation for cosmic baryon asymmetry.

2HDM and Sources of CP Violation. To be specific, we consider the type-II 2HDM, with the Higgs potential

$$\begin{aligned} V = & \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) \\ & + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \text{h.c.}\right] \\ & - \frac{1}{2}\left\{m_{11}^2(\phi_1^\dagger\phi_1) + \left[m_{12}^2(\phi_1^\dagger\phi_2) + \text{h.c.}\right] + m_{22}^2(\phi_2^\dagger\phi_2)\right\}. \end{aligned} \tag{1}$$

The Higgs doublets $\phi_{1,2}$ are defined with hypercharge 1. The tree-level flavor-changing neutral currents (FCNC) can be suppressed by imposing a Z_2 symmetry [9] ($\phi_1 \to -\phi_1$ and $\phi_2 \to \phi_2$) which is softly broken by m_{12}. Under this approximate symmetry, the only complex parameters in the potential are λ_5 and m_{12}^2, and we are free to start from the basis where λ_5 is made real by proper rotation of $\phi_{1,2}$ phases.

The corresponding Yukawa couplings respecting the Z_2 symmetry are

$$\mathcal{L}_Y = \bar{Q}_L Y_D \phi_1 D_R + \bar{Q}_L Y_U (i\tau_2)\phi_2^* U_R + \bar{L}_L Y_E \phi_1 E_R \ , \quad (2)$$

where D_R or E_R (U_R) is defined to be odd (even) under this Z_2 symmetry. The Higgs vacuum expectation values (VEV) are generally complex, with a relative phase ξ

$$\langle\phi_1\rangle = \begin{pmatrix} 0 \\ v\cos\beta/\sqrt{2} \end{pmatrix}, \ \ \langle\phi_2\rangle = \begin{pmatrix} 0 \\ v\sin\beta e^{i\xi}/\sqrt{2} \end{pmatrix} \ . \quad (3)$$

The minimum condition of the potential solves ξ from the phase of m_{12}^2 (recall λ_5 is real)

$$\mathrm{Im}\,(m_{12}^2 e^{i\xi}) = (\lambda_5 \sin 2\xi) v^2 \sin\beta\cos\beta \ , \quad (4)$$

which means there exists only one independent physical CP phase.

In this model, the source of CP violation arise from the neutral Higgs sector (we define $\sqrt{2}\phi_1^0 = H_1^0 + iA_1^0$, $e^{-i\xi}\sqrt{2}\phi_2^0 = H_2^0 + iA_2^0$ with H_i^0, A_i^0 being real fields). Namely, the physical CP-odd state $A^0 = -\sin\beta A_1^0 + \cos\beta A_2^0$ will mix with the even states H_1^0, H_2^0. The off-diagonal elements of the mass square matrix $\mathcal{M}$ are proportional to $\lambda_5 \sin 2\xi\, v^2$. The mass square matrix in the basis of (H_1^0, H_2^0, A^0) can be diagonalized with a real orthogonal R, defined as $R\mathcal{M}R^{\mathrm{T}} = \mathrm{diag}(M_{h_1}^2, M_{h_2}^2, M_{h_3}^2)$

$$R = \begin{pmatrix} -s_\alpha c_{\alpha_b} & c_\alpha c_{\alpha_b} & s_{\alpha_b} \\ s_\alpha s_{\alpha_b} s_{\alpha_c} - c_\alpha c_{\alpha_c} & -s_\alpha c_{\alpha_c} - c_\alpha s_{\alpha_b} s_{\alpha_c} & c_{\alpha_b} s_{\alpha_c} \\ s_\alpha s_{\alpha_b} c_{\alpha_c} + c_\alpha s_{\alpha_c} & s_\alpha s_{\alpha_c} - c_\alpha s_{\alpha_b} c_{\alpha_c} & c_{\alpha_b} c_{\alpha_c} \end{pmatrix} \quad (5)$$

with $c_\alpha = \cos\alpha$, $s_\alpha = \sin\alpha$. In the CP conserving limit, $\alpha_{b,c} \to 0$. In the decoupling limit of second doublet, $\alpha \to \beta - \pi/2$ and $\alpha_{b,c} \to 0$.

The lightest neutral scalar h_1, which we take to be the SM-like Higgs, with mass $M_1 = 125\,\mathrm{GeV}$, is the following linear combination [10],

$$h_1 = -\sin\alpha\cos\alpha_b H_1^0 + \cos\alpha\cos\alpha_b H_2^0 + \sin\alpha_b A^0 \ , \quad (6)$$

Using the Yukawa coupling structure in Eq. (2), we obtained the couplings of h_1 to fermions

$$\begin{aligned}\mathcal{L}_{h_1 f\bar{f}} = &\frac{m_t}{v\sin\beta} h_1 \left[\cos\alpha\cos\alpha_b \bar{t}t - \sin\alpha_b\cos\beta\bar{t}i\gamma_5 t\right] \\ &+ \frac{m_b}{v\cos\beta} h_1 \left[-\sin\alpha\cos\alpha_b \bar{b}b - \sin\alpha_b \sin\beta \bar{b}i\gamma_5 b\right] . \quad (7)\end{aligned}$$

The interactions with gauge bosons WW and ZZ are

$$\mathcal{L}_{h_1VV} = \cos\alpha_b \sin(\beta-\alpha)\mathcal{L}_{hVV}^{\mathrm{SM}} \equiv a\mathcal{L}_{hVV}^{\mathrm{SM}} \ . \quad (8)$$

It is worth pointing out the CP violating coupling of the lightest Higgs boson h_1 only depends on α_b, and is closely connected to the phase ξ. In order to make their relation more transparent, consider the case $m_{h_2} \approx m_{h_3} \gg m_{h_1}$, we find approximately

$$\tan\alpha_b \approx \frac{-\lambda_5 \sin 2\xi\, v^2}{m_{h^+}^2 + (\lambda_4 - \lambda_5\cos 2\xi)v^2/2} \ , \quad (9)$$

where h^+ is the physical charged Higgs state. With the second doublet near the weak scale, we would expect

$$\alpha_b \sim \xi \ . \quad (10)$$

This is the key relation that motivates our study below. The angle α_b are constrained by the Higgs property and the electric dipole moment experiments, while the phase ξ is closely connected to the phase jump across the bubble wall during the electroweak phase transition. The latter gives the essential CP violating source for baryogenesis.

Higgs Properties as Indirect Probe. From the derived interactions (7) and (8), we can obtain the modified Higgs production and decay rates at the LHC.

The Higgs production via gluon fusion process could happen through both h_1GG and $h_1G\widetilde{G}$ operators in an incoherent way, after integrating out the CP conserving and violating $h_1t\bar{t}$, $h_1b\bar{b}$ interactions. The ratio of the two cross sections is [11, 12]

$$\frac{\sigma_{gg\to h_1}}{\sigma_{gg\to h_1}^{\mathrm{SM}}} = \frac{(1.03c_t - 0.06c_b)^2 + (1.57\tilde{c}_t - 0.06\tilde{c}_b)^2}{(1.03-0.06)^2}, \quad (11)$$

for $m_{h_1} = 125\,\mathrm{GeV}$, and the coefficients are

$$\begin{aligned} c_t &= \frac{\cos\alpha}{\sin\beta}\cos\alpha_b \ , \quad c_b = -\frac{\sin\alpha}{\cos\beta}\cos\alpha_b \ , \\ \tilde{c}_t &= -\cot\beta\sin\alpha_b \ , \quad \tilde{c}_b = -\tan\beta\sin\alpha_b \ . \end{aligned} \quad (12)$$

The above coefficients are universal for all up- and down-type fermions, respectively. The SM limit corresponds to $a = c_b = c_t = 1$, $\tilde{c}_t = \tilde{c}_b = 0$. The production cross sections of h_1 via W, Z boson fusion and in association with W, Z are simply rescaled from the SM case by $\sigma_{VV\to h_1}/\sigma_{VV\to h}^{\mathrm{SM}} = \sigma_{Vh_1}/\sigma_{Vh}^{\mathrm{SM}} = a^2$.

The decay rates into gauge bosons are rescaled by $\Gamma_{h_1\to WW}/\Gamma_{h\to WW}^{\mathrm{SM}} = \Gamma_{h_1\to ZZ}/\Gamma_{h\to ZZ}^{\mathrm{SM}} = a^2$. The decay rates into light fermions are approximately $\Gamma_{h_1\to b\bar{b}}/\Gamma_{h\to b\bar{b}}^{\mathrm{SM}} = \Gamma_{h_1\to\tau^+\tau^-}/\Gamma_{h\to\tau^+\tau^-}^{\mathrm{SM}} \approx c_b^2 + \tilde{c}_b^2$, by neglecting the final state masses. Similar to the gluon fusion case, the decay into two photons can be separated into CP conserving and violating parts

$$\frac{\Gamma_{h_1\to\gamma\gamma}}{\Gamma_{h\to\gamma\gamma}^{\mathrm{SM}}} = \frac{(0.23c_t - 1.04a)^2 + (0.35\tilde{c}_t)^2}{(0.23-1.04)^2} \ . \quad (13)$$

Finally, for calculating the Higgs total decay width, the decay to gluons is $\Gamma_{h_1\to gg}/\Gamma_{h\to gg}^{\mathrm{SM}} = \sigma_{gg\to h_1}/\sigma_{gg\to h_1}^{\mathrm{SM}}$.

With the above rescaling, we proceed to make a global fit to the inclusive LHC Higgs data published in March 2013 [3, 4], taking into account the possibility that CP could be violated in the Higgs sector. The most significant change in the latest data is that CMS is no longer seeing an excess in the diphoton channel, while it still persists in the ATLAS result. Therefore, we decided to show both the separate and the combined fits to the ATALS and CMS data. The best fit points in the effective operator coefficieints a, c_t, $\tilde{c}_t$, c_b, $\tilde{c}_b$ and the 2HDM

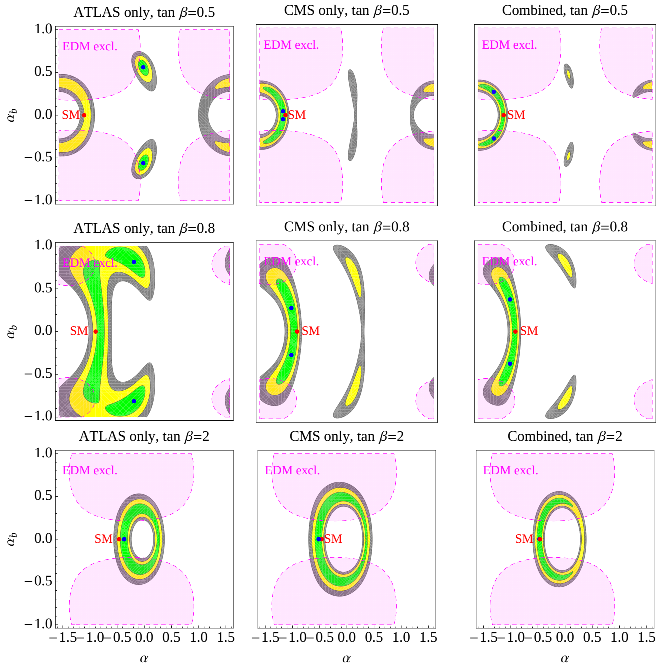

FIG. 1: Global fits to the Higgs data for various values of $\tan\beta$. The global minima still prefers a non-vanishing α_b for $\tan\beta \lesssim 1$. The magenta region is excluded by electron EDM constraint.

parameter α, α_b for $\tan\beta = 0.8$ are presented in Table I. A more comprehensive analysis on the 2HDM parameter α, α_b and $\tan\beta$ which includes the exclusion region from the EDM constraints (see below) are shown in Fig. 1. It is clear to see that SM gives the best fit for $\tan\beta > 1$. For $\tan\beta \lesssim 1$, better fit points can be found with a non-vanishing CP phase α_b.

In the presence of CP violating Higgs couplings with the top quark $\tilde{c}_t$, incoherent contributions in Eqs. (11) and (13) can modify both the production $gg \to h_1$ and the $h_1 \to \gamma\gamma$ decay rate [13]. For smaller $\tan\beta \lesssim 1$ and $\alpha \approx 0$, larger $\tilde{c}_t$ and smaller c_b, $\tilde{c}_b$ can be achieved simultaneously, with an order one CP phase α_b. The resulting signal strengths are characterized by an enhanced diphoton rate, and a suppressed $Vb\bar{b}$ rate, both favored by the ATLAS data. (see the first column of Fig. 1). The common features of such minimum include: 1) enhanced effective hgg coupling r_g, 2) suppressed $\tilde{c}_t$, $\tilde{c}_b$, a couplings, and the effective $h\gamma\gamma$ coupling r_g, 3) reduced Higgs total width. These effects are optimized for $\tan\beta \sim 1$. On the other hand, the signals observed by CMS are SM-like. Therefore, the best fit point always lies close to SM. For $\tan\beta < 1$, a nonzero α_b gives better fit, because it can accommodate the slight suppression in the WW and ZZ channel.

Electric Dipole Moments The mixing α_b between the CP even and odd Higgs states leads to a series of low-energy CP violating variables, among which we find the EDM of electron gives the leading constraints. The dominant contribution to electron EDM comes from the Barr-Zee type diagrams at two loop [14]. The lightest Higgs boson can mediate CP violation from the top quark and W loops to the electron line [15, 16],

	α	$\lvert\alpha_b\rvert$	c_t	$\tilde{c}_t$	c_b	$\tilde{c}_b$	a
			$R_{\gamma\gamma}$	R_{WW}	R_{ZZ}	R_{Vbb}	$R_{\tau\tau}$
ATLAS	−0.19	0.81	1.08	−0.91	0.17	−0.58	0.52
			1.35	1.28	1.28	0.47	1.71
CMS	−1.00	0.27	0.83	−0.33	1.04	−0.21	0.96
			0.91	0.83	0.83	0.93	1.02
Combined	−0.99	0.37	0.82	−0.45	1.00	−0.29	0.93
			1.05	0.86	0.86	1.02	1.18

TABLE I: Best fit points with $\tan\beta = 0.8$. ATLAS: $\chi^2_{\rm min} - \chi^2_{\rm SM} = -3.27$. CMS: $\chi^2_{\rm min} - \chi^2_{\rm SM} = -1.74$. Combined: $\chi^2_{\rm min} - \chi^2_{\rm SM} = -0.39$. A nonzero CP violating phase is welcomed by the data.

$$\left[\frac{d_e}{e}\right]_t = \frac{16\sqrt{2}\alpha G_F m_e}{3(4\pi)^3} \times \Big(f(z_t)\tan^2\beta \mathrm{Im} Z_2 - g(z_t)\cot^2\beta \mathrm{Im} Z_1\Big), \quad (14)$$

$$\left[\frac{d_e}{e}\right]_w = \frac{2\sqrt{2}\alpha G_F m_e}{(4\pi)^3}\Big(3f(z_w) + 5g(z_w)\Big) \times (\sin^2\beta\tan^2\beta \mathrm{Im} Z_2 + \cos^2\beta \mathrm{Im} Z_1), \quad (15)$$

where $z_t = m_t^2/M_{h_1}^2$, $z_w = M_W^2/M_{h_1}^2$ and the loop functions $f(z)$ and $g(z)$ can be found in [14],

In the above formulae, the CP violating variables defined in [17] can be expressed in terms of c_e, $\tilde{c}_e$, c_t, $\tilde{c}_t$, a defined in Eqs. (8) and (12) for the Higgs global fits,

$$\begin{aligned} \tan^2\beta \mathrm{Im}\, Z_2 &= -\tilde{c}_b c_t\,, \\ \cot^2\beta \mathrm{Im}\, Z_1 &= \tilde{c}_t c_b\,, \\ (\sin^2\beta\tan^2\beta \mathrm{Im} Z_2 + \cos^2\beta \mathrm{Im} Z_1) &= a\,\tilde{c}_b\,, \end{aligned} \quad (16)$$

where we have used the fact that down type fermions have universal rescaling in the Higgs couplings. Notice in the EDM, these coefficients always appear in the product $\tilde{c}c'$ or $\tilde{c}a$, i.e., P and CP are violated when h_1 is attached to either the top quark loop or the external fermion line.

We find the top and W-loop contributions to electron EDM most of the time have opposite signs, and can be minimized simultaneously near $\alpha \approx \beta$. The magnitude of the W-loop part is more sensitive to $\tan\beta$, and the maximal cancellation happens near $\tan\beta \sim 1$. In these regimes, the electron EDM limit can be satisfied without suppressing the CP violating phase α_b. These features are illustrated in Fig. 2. We use the 95% confidence level limit of the latest electron EDM measurement [18], $d_e < 1.25 \times 10^{-27}\, e\,\mathrm{cm}$. The exclusion in $\alpha - \alpha_b$ parameter space is shown as the magenta region in Fig. 1.

We have also considered the neutron EDM constraints, which receives contributions from valence quark EDM, and indirectly from valence quark chromoelectric dipole moment and the Weinberg operators. We find they do not impose more relevant constraint than the electron EDM. This is partially due to the less stringent experimental bound [19], and partially due to smaller electric charges of the quarks, or the suppression of Wilson coefficients in the QCD evolution from the weak scale to GeV.

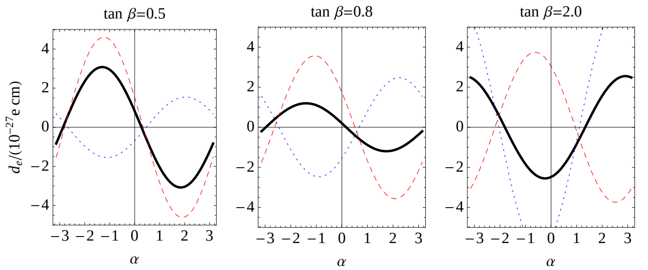

FIG. 2: Electron EDM as a function of the angle α, for $\tan\beta = 0.5, 0.8, 2$ respectively, and with CP violating phase $\alpha_b = 0.5$ fixed. The dashed (dotted) curves corresponds to the virtue top-loop (W-loop) contribution.

So far we have neglected the charged and other neutral Higgs states in both the Higgs fit and the EDM calculation, which can be justified as following. The charged Higgs mass is constrained by $b \to s\gamma$ transition [20] and the measurement of the R_b coupling at LEP [21, 22], to be heavier than 300–400 GeV. Moreover, the neutral ($h_{2,3}$) and charged Higgs need to be heavier than 300 GeV in order to get a strong first-order phase transition [23, 24].

Electroweak Baryogenesis. At high temperature, the Higgs VEVs are generally complex and their phases vary across the bubble that separates the broken and symmetric phase in a first-order electroweak phase transition. This implies the top quark mass has a space-time dependent phase during the electroweak phase transition, and results in a CP violation source for baryogenesis proportional to the derivative of the phase. This CP violation sources can be estimated as [25, 26]

$$S_t(z) \approx \frac{3}{2\pi^2}\left(\frac{m_t}{v\sin\beta}\right)^2 v_T^2(z)\theta'(z)v_w T\,, \qquad (17)$$

where we take $L_w = 3/T$ and $v_w = 0.03$, and $z < 0$ (> 0) corresponds to unbroken (broken) side of the expanding bubble. We assume the following shapes of the bubble wall and the complex phase, $v_T/T = [1+\tanh(z/L_w)]/(2\sqrt{2})$ and $\theta(z) = \theta_{\rm brk} - \Delta\theta[1-\tanh(z/L_w)]/2$ [27], where $\Delta\theta$ is the change in the VEV's phase from the broken to unbroken side of the bubble.

The imbalance between particle and antiparticle number densities caused by CP violation prevails among the quarks and Higgs fields, through the top Yukawa interaction, mass term and strong sphaleron processes. This results in a net asymmetry in the left-handed fermion charge density n_L, which is also non-vanishing into the unbroken phase due to the diffusion [28]

$$n_L(z<0) \approx -\frac{27}{2}\frac{v_w^2}{\Gamma_{ss}\bar{D}}\left(1-\frac{D_q}{\bar{D}}\right)\mathcal{A}\, e^{v_w z/\bar{D}}\,, \qquad (18)$$
$$\mathcal{A} = 14/(23\bar{D}\kappa_+)\int_0^{L_w} S_t(z)e^{\kappa_+ z}dz\,,$$

where $\kappa_+ = (v_w + \sqrt{v_w^2 + 4\bar{\Gamma}\bar{D}})/(2\bar{D})$ and $\bar{D} \approx 75/T$, $\bar{\Gamma} = (7/46)(\Gamma_m + \Gamma_h)$. The relevant thermal rates are $\Gamma_{ss} = 16\kappa\alpha_s^4 T$ (we take $\kappa = 20$ from [29]), $\Gamma_{ws} = 120\alpha_w^5 T$ [30], $\Gamma_h(z) \approx \Gamma_m(z) = (3/2\pi^2)\,(m_t/v\sin\beta)^2\, v_T^2(z)/T$. Clearly, the charge asymmetry n_L is suppressed by the chirality-changing QCD sphaleron rate Γ_{ss} [29].

In the unbroken phase near the bubble, the baryon number breaking weak sphaleron process is still operating and can convert the nonzero chiral charge into baryon asymmetry. The weak sphaleron rate is much lower than the expansion rate of the bubble, and the final baryon number can be estimated as

$$n_b = -\frac{3\Gamma_{ws}}{2v_w}\int_{-\infty}^0 n_L(z)e^{15\Gamma_{ws}z/(4v_w)}dz\,. \qquad (19)$$

We find the observed baryon asymmetry to entropy density ratio $\eta_b = n_b/s \approx (0.7-0.9)\times 10^{-10}$ [31, 32] can be obtained with $\Delta\theta$ around 0.05 (see Fig. 3). Numerical studies [23, 33] have shown $\Delta\theta$ is of similar size to the zero temperature phase ξ, and therefore α_b from Eq. (10). Successful baryogenesis sets a lower bound on the CP violating phase. Such phase will keep being probed directly or indirectly in the future LHC Higgs measurements and low energy experiments like EDM, and will test or challenge the viability of the electroweak baryogenesis scenario. We do notice though the final baryon number density is sensitive to the choices of wall velocity v_w and the strong sphaleron rate Γ_{ss}, etc.. A more precise calculation of η_b would require improved determination of these quantities which involves higher-order and non-perturbative calculations.

Direct Probe of CP Violation in Higgs sector. Here we briefly discuss the prospects of measuring the CP violation in the Higgs sector. The $h \to ZZ^* \to 4\ell$ data have been used to constrain the CP odd coupling to Z-boson [34] (See also [35], [36]). Notice that this operator $hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$ is dimension five and their physical effects are considerably small comparing to those from the tree level CP even coupling so the current data cannot set a relevant limit. The physical effects from operators $hA_{\mu\nu}\tilde{A}^{\mu\nu}$ or $hZ_{\mu\nu}\tilde{A}^{\mu\nu}$ in the 2γ and $Z\gamma$ channel could be comparable with those from the CP even operators but such discriminations require the knowledge of photon polarization which is difficult to measure at the LHC. A more promising channel could be the gluon fusion production of h in together with two forward jets, and studying the azimuthal angle correlation between the two jets [37]. A similar channel would be the $t\bar{t}h$ production [38]. It has also been proposed the virtual effect of a CP violating Higgs coupling can be probed in the top quark pair production and leptonic decay channel [39]. We leave a more systematic classification and quantitative study of these signatures employing the LHC data for a future work.

Conclusion. In summary, we have worked in the type-II 2HDM where the sources of CP violation beyond the CKM matrix can be parametrized with a single phase. We performed a global fit to the latest LHC Higgs data, and find a nonzero CP phase is favored for $\tan\beta \lesssim 1$. When combined with the electron and neutron EDM constraints, we find the phase is allowed to be as large as order one near $\tan\beta \sim 1$. This phase can provide the CP violating source for electroweak baryoge-

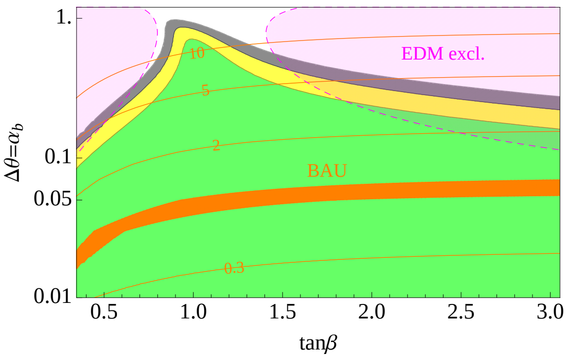

FIG. 3: Values of $\Delta\theta$ and $\tan\beta$ consistent with the observed baryon asymmetry of the universe. We take the constraints from Fig. 1 which point to $\alpha \approx \beta - \pi/2$, and assumed $\Delta\theta = \alpha_b$.

nesis which explains the baryon asymmetry of the universe. The future improvements in measuring the higgs properties at LHC and the EDMs will enable us to probe the viability of electroweak baryogenesis.

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Note added. While this paper is being finalized, Ref. [7] appeared which also discussed Higgs global fit in the CP violating case. Nevertheless, their results are based on one Higgs doublet with universal fermion couplings.

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